A Robust Sliding Mode Controller for an AC Electric Drives

Guided By:
Prof. J. V. Desai
Dean of CET-Mody University

Co-Supervisor:
Dr. Bharat Singh Rajpurohit
Associate Professor
School of Computing & Electrical Engg.
Indian Institute of Technology Mandi

Presented By:
Mrs.Ritu Tak
Enrolment No.: 130470
Phd. Student

Electrical Drives

Whenever the term electric motor or generator is used, we tend to think that the speeds of rotation of these machines are totally controlled only by the applied voltage and frequency of the source current. But the speed of rotation of an electrical machine can be controlled precisely also by implementing the concept of drive. The main advantage of this concept is, the motion control is easily optimized with the help of drive. In very simple words, the systems which control the motion of the electrical machines are known as electrical drives.

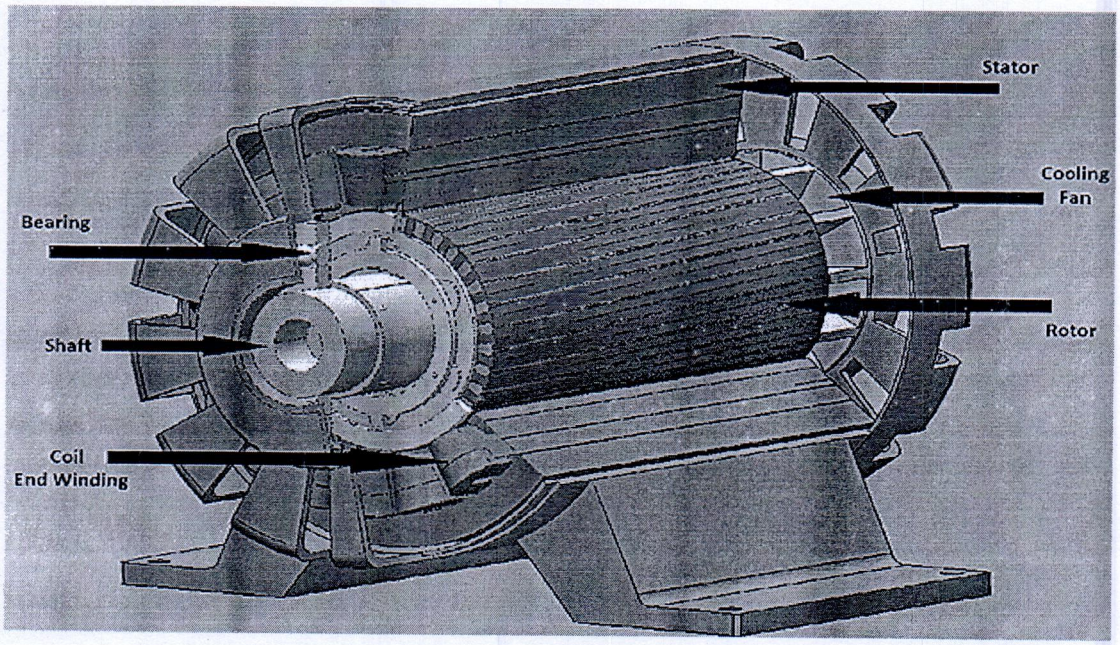
The electric drive system is widely used in large number of industrial and domestic applications like factories, transportation systems, textile mills, fans, pumps, motors, robots etc.

Comparison of different kinds of Motors:

- When the electrical drives were not so popular, **induction** and **synchronous** motors were usually implemented only where fixed or constant speed .
- For variable speed drive applications, dc motors were used.
- But as we know that, induction motors of same rating as a dc motor have various advantages like they have **lighter weight, lower cost, lower volume** and there is **less restriction on maximum voltage, speed and power ratings.** For these reasons, the induction motors are rapidly replaced the dc motors.
- Moreover induction motors are **mechanical stronger** and **requires less maintenance**.
- When synchronous motors are considered, wound field and permanent magnet synchronous motors have higher full load efficiency and power factor than induction motors, but the size and cost of synchronous motors are higher than induction motors for the same rating.

Induction Motor Control

The induction motor (IM) is widely used in the industry, due to its reliability, maintenance-free operation and relatively low cost. However, precise and fast control of the flux and of the speed (or torque) is not simple to obtain, due to the complex multivariable nonlinear dynamics, to the unavailability of the rotor electrical quantities and to the parameter variations that occur during working conditions, this make the control of induction motor is a challenging problem and has attracted much attention.

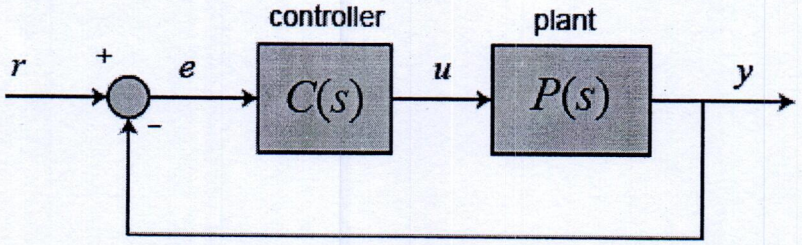


Control Strategies

- Over the years, **field-oriented control** has been recognized as the algorithm that gives the best dynamic performance to the IM drive. Using this method, the knowledge of rotor speed and flux is necessary. Tachogenerators or digital shaft-position encoders are usually used to detect the rotor speed of motors.
- Speed sensors lower the system reliability and require special attention to noise. Recently many researches' have been carried on the design of speed sensorless control schemes. In this work the speed is obtained based on the measurement of stator voltages and currents.
- However, the estimation is usually complex and heavily dependent on machine parameters. Therefore, although sensorless vector-controlled drives are commercially available at this time, **the parameter uncertainties impose a challenge in the control performances.**

PID Controllers

Consider the following unity feedback system:
The output of a PID controller, equal to the control input to the plant, in the time-domain is as follows:



$$u(t) = K_p e(t) + K_i \int e(t)dt + K_p \frac{de}{dt}$$

The variable (e) represents the tracking error, the difference between the desired input value (r) and the actual output (y). This error signal (e) will be sent to the PID controller, and the controller computes both the derivative and the integral of this error signal.

Kp = Proprotional gain ; Ki = Integral gain ; Kd = Derivative gain

The Characteristics of P, I, and D Controllers:

- ***Kp*** = Reduce the rise time but never eliminate the steady-state error.
- ***Ki*** = eliminating the steady-state error, but it may make the transient response slower.
- ***Kd*** = Increasing the stability of the system, reducing the overshoot, and improving the transient response.

Note that these correlations may not be exactly accurate, because *Kp*, *Ki*, and *Kd* are dependent on each other. In fact, changing one of these variables can change the effect of the other two.

PID controller linear zing a nonlinear model around the operating steady-state and then computing values of the controller parameters that incorporate stability, performance and robustness objective in the closed-loop system.

Limitations of PID Controller:

- The PID controller is widely used in vector control of induction motors due to its good performance and simple structure. However in some application the PID controller cannot meet the concerned robustness under parameter variation and external load disturbance.
- The machine parameters depend generally on the operating point and vary either on the temperature (resistance), or with the magnetic state of the induction machine. These parametric variations modify the performances of the control system when we use a regulator or a control law with fixed parameters.

Some alternative and complementary techniques to particular classed of nonlinear control problem are listed below:

- **Feedback Linearization:** In this method the plant is first linearized and then a linear controller is added to the feedback linearized system to achieve the desired control goals.

Drawback: It requires full state measurement and does not guarantee robustness in presence of parameter uncertainties or disturbance.

- **Adaptive Control:** This method deals with uncertain systems or time-varying systems. They parameterize the uncertainty in terms of certain unknown parameters and use feedback to learn these parameters on-line, during the operation of the system.

Drawback: Nothing is said about the transient response of the system and uncertain nonlinearity coming from disturbances and unmodeled dynamics are not considered, and the system may lose stability even when a small disturbance appears.

Sliding mode control

The new industrial applications necessitate speed variations having high dynamic performances, high capacity of overload in the whole range of speed and robustness to different perturbations. Thus, the recourse to robust control algorithms is desirable in stabilization and in tracking trajectories. The Sliding mode control approach is recognized as one of the efficient tools to design robust controllers for complex high-order nonlinear dynamic plant operating under uncertainty conditions.

The ***Siding mode control*** can offer many good properties, such as:

- Good performance against unmodeled dynamics.
- Insensitive to parameter variation.
- External disturbance rejection
- Fast dynamic response

These advantages of sliding mode control can be employed in the position and speed control of an Induction Motor. The principle of SMC is to alter system dynamics along some surfaces in the state space so that the system state is attracted to these surfaces and maintained on them thereafter.

Concept of Sliding Mode:

Let us apply the proposed algorithm to simple nonlinear model. The simple nonlinear system equation is as follows:

$$\ddot{x} + a(t)\dot{x}^2 \cos 3x = u$$

Where a(t) is unknown but verifies

$$1 \le a(t) \le 2$$

Assume $a(t)=1.5$

Let as design the sliding mode control as follows:

$$s = \dot{\tilde{x}} + \lambda \tilde{x}$$

Here s is simply the sum of position error and velocity error.

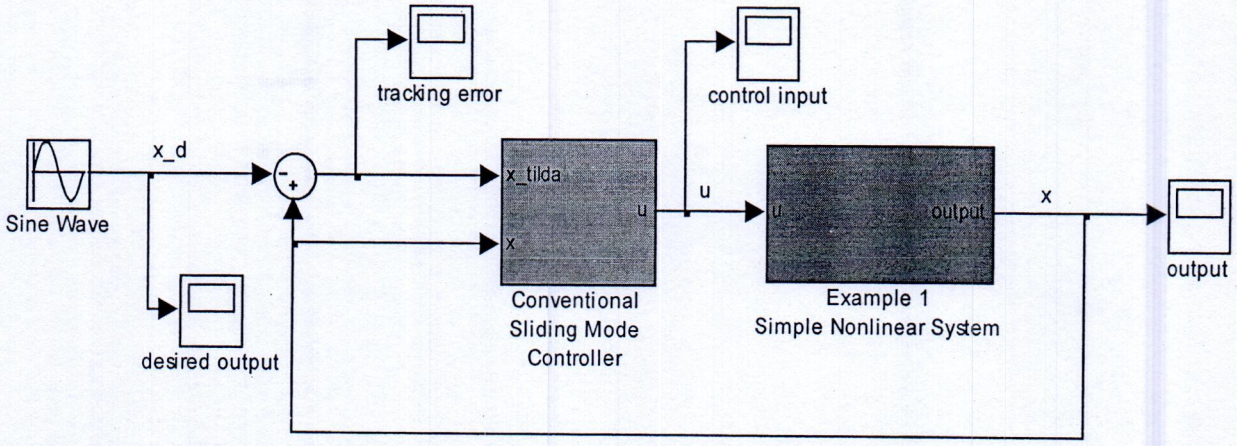
The control input is:

$$u = -\hat{f} + \ddot{x}_d - \lambda \dot{\tilde{x}} - k\,\mathrm{sgn}(s), \quad k = F + \eta$$

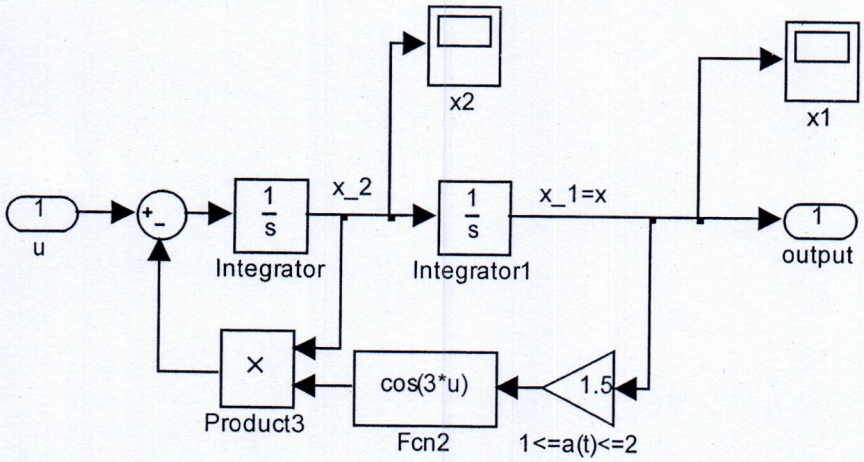
Where,

$$\hat{f} = -1.5\dot{x}^2 \cos(3x) \qquad F = 0.5\dot{x}^2 \left|\cos(3x)\right| \qquad x_d = \sin\frac{\pi t}{2}$$

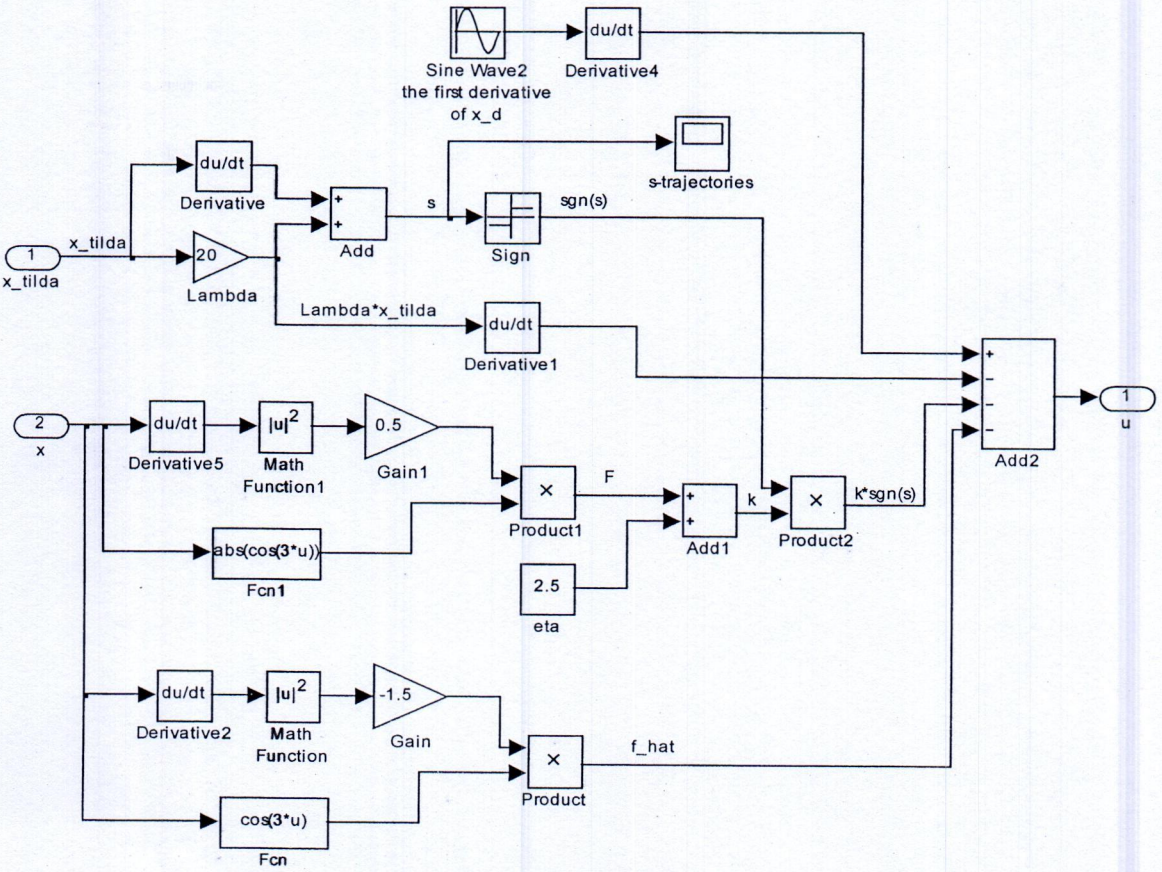
Simulation in Matlab Software:



Simulink model of nonlinear plant:

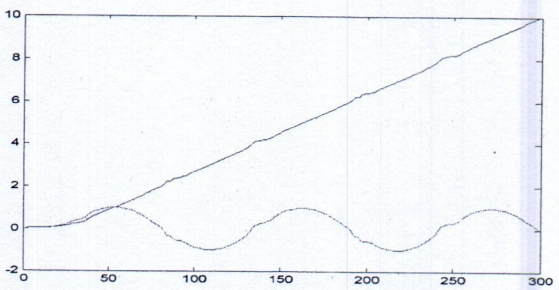


Simulink model of sliding mode controller:

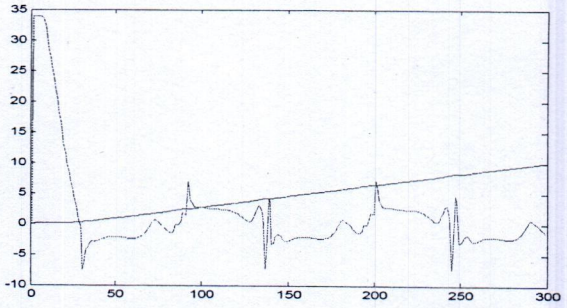


Simulation Result:

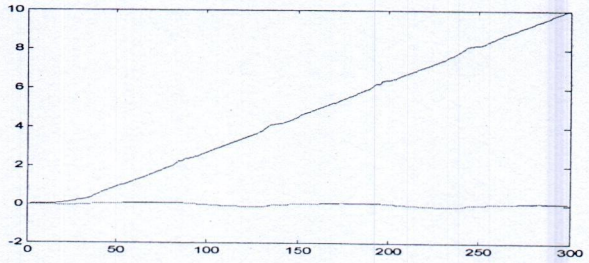
- **Desired output**



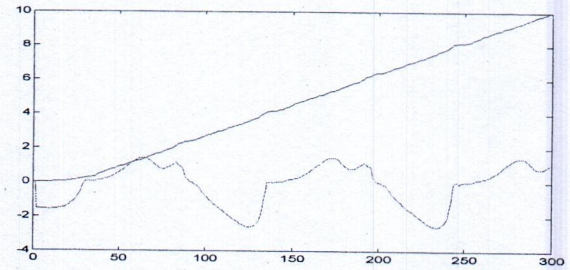
- **Control input**



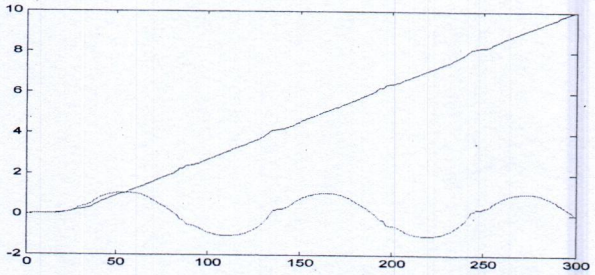
- **Tracking error**



- **S-trajectories**



- **Output**



Mathematical model of induction motor:

The state space model of induction motor in the dq coordinate is given by

$$\frac{di_{sd}}{dt} = -a_1 i_{sd} + \omega_s i_{sq} + a_2 \Psi_{rd} + a_3 \omega \Psi_{rq} + a_4 u_{sd} \quad (1)$$

$$\frac{di_{sq}}{dt} = -\omega_s i_{sd} - a_1 i_{sq} - a_3 \omega \Psi_{rd} + a_2 \Psi_{rq} + a_4 u_{sq} \quad (2)$$

$$\frac{d\Psi_{rd}}{dt} = a_5 i_{sd} - a_5 \Psi_{rd} + (\omega_s - \omega)\Psi_{rq} \quad (3)$$

$$\frac{d\Psi_{rq}}{dt} = a_5 i_{sq} - (\omega_s - \omega)\Psi_{rd} - a_5 \Psi_{rq} \quad (4)$$

$$T_e = a_6 [\Psi_{rd} i_{sq} - \Psi_{rq} i_{sd}] \quad (5)$$

$$\frac{d\omega}{dt} = a_7 [T_e - T_L] \quad (6)$$

Where ω is the rotor speed (rad/s), T_e is the motor torque (Nm), T_L is the load torque (Nm), ω_s is the angular frequency of the stator current (rad/s),

$$a_1 = \left(\frac{1}{\sigma T_s} + \frac{1-\sigma}{\sigma T_r}\right), \quad a_2 = \frac{1-\sigma}{\sigma T_r}, \quad a_3 = \frac{1-\sigma}{\sigma} \quad (7)$$

$$a_4 = \frac{1}{\sigma L_s}, \quad a_5 = \frac{1}{T_r}, \quad a_6 = \frac{3pL_m^2}{2L_r}, \quad a_7 = \frac{pa_6}{J} \quad (8)$$

$$\sigma = 1 - \frac{L_m^2}{L_s L_r}, \quad T_s = \frac{L_s}{R_s}, \quad T_r = \frac{L_r}{R_r} \quad (9)$$

R_s is the stator resistance, R_r is the rotor resistance, L_s is the stator inductance, L_r is the rotor inductance, L_m is the mutual inductance, p is the number of pole pairs, and J is the moment of inertia of the rotor.

Design of the switching function

The control objective is to regulate the rotor flux ψ_r and the rotor speed ω to the set point.

$$\Psi_r = \sqrt{\Psi_{rd}^2 + \Psi_{rq}^2} \qquad (10)$$

Let

$$\phi = \Psi_{rd}^2 + \Psi_{rq}^2 \qquad (11)$$

We have

$$\dot{\phi} = 2(\Psi_{rd}\dot{\Psi}_{rd} + \Psi_{rq}\dot{\Psi}_{rq}) \qquad (12)$$

$$\ddot{\phi} = 2a_5(\dot{i}_{sd}\Psi_{rd} + i_{sd}\dot{\Psi}_{rd} + \dot{i}_{sq}\Psi_{rq} + i_{sq}\dot{\Psi}_{rq} - 2[\Psi_{rd}\dot{\Psi}_{rd} + \Psi_{rq}\dot{\Psi}_{rq}])$$

$$= 2a_5(-[a_1 + 3a_5][i_{sd}\Psi_{rd} + i_{sq}\Psi_{rq}] + \omega[i_{sd}\Psi_{rq} - i_{sq}\Psi_{rd}] + [a_2 + 2a_5]\Psi_r^2 + a_5[i_{sd}^2 + i_{sq}^2] + 2\omega_s[i_{sq}\Psi_{rd} - i_{sd}\Psi_{rq}] + a_4[u_{sd}\Psi_{rd} + u_{sq}\Psi_{rq}]) \qquad (13)$$

$$\dot{T}_e = a_6(\dot{\Psi}_{rd}i_{sq} + \Psi_{rd}\dot{i}_{sq} - \dot{\Psi}_{rq}i_{sd} - \Psi_{rq}\dot{i}_{sd})$$

$$= a_6(-a_5[i_{sd}\Psi_{rq} + i_{sq}\Psi_{rd}] + a_1[i_{sd}\Psi_{rq} - i_{sq}\Psi_{rd}] + \omega[i_{sd}\Psi_{rd} - i_{sq}\Psi_{rq}] - a_3\omega\Psi_r^2 + a_4[u_{sd}\Psi_{rd} + u_{sq}\Psi_{rq}]) \qquad (14)$$

(12), (13), (14) show that the relative degrees of the system with output signals Φ and T_e are respectively, 2 and 1.

Let

$$e_\phi = \phi_{ref} - \phi$$

and

$$e_T = T_{ref} - T_e$$

The sliding surface is defined as follows

$$S_1 = \tau_\phi \dot{e}_\phi + e_\phi$$
$$= \tau_\phi(\dot{\phi}_{ref} - \dot{\phi}) + (\phi_{ref} - \phi) \quad (15)$$

$$S_2 = e_T = T_{ref} - T_e \quad (16)$$

Where $\tau\varphi > 0$ is the time constant of the sliding mode of Φ . Since is a constant.

SMC BASED CONTROLLER LAW:

We have

$$\dot{S}_1 = -\tau_\phi \ddot{\phi} - \dot{\phi} \quad (17)$$

$$\dot{S}_2 = \dot{e}_T = \dot{T}_{ref} - \dot{T}_e \quad (18)$$

Inserting (12), (13), (14) into (17) and (18), we get

$$\begin{bmatrix} \dot{S}_1 \\ \dot{S}_2 \end{bmatrix} = \begin{bmatrix} f_{11} \\ \dot{T}_{ref} + f_{21} \end{bmatrix} + \begin{bmatrix} f_{12} & f_{13} \\ f_{22} & f_{23} \end{bmatrix} \begin{bmatrix} u_{sd} \\ u_{sq} \end{bmatrix} \quad (19)$$

Where

$$f_{11} = -2\tau_\phi [a_5^2 (i_{sd}^2 + i_{sq}^2 - i_{sd} - i_{sq}) + \\ + a_5(\omega_s - \omega)(i_{sq} - i_{sd} + 2\Psi_{rd} - 2\Psi_{rq}) + \\ + (a_5^2 + a_2 a_5 + (\omega_s - \omega)^2)\Psi_r^2 + \\ - 2a_5(a_1 + a_5)(i_{sd}\Psi_{rd} + i_{sq}\Psi_{rq}) + \\ + a_5(\omega_s - 2\omega)(i_{sd}\Psi_{rq} - i_{sq}\Psi_{rd}) + \\ + (a_5^2 - (\omega_s - \omega)^2)(\Psi_{rd} + \Psi_{rq})] + \\ - 2[a_5 i_{sd}\Psi_{rd} + a_5 i_{sq}\Psi_{rq} - a_5\Psi_r^2] \qquad (20)$$

$$f_{12} = -2\tau_\phi a_4 a_5 \Psi_{rd}\ ,\ f_{13} = -2\tau_\phi a_4 a_5 \Psi_{rq} \qquad (21)$$

$$f_{21} = -a_6[-(a_1 + a_5) i_{sq}\Psi_{rd} + (a_1 - a_5) i_{sd}\Psi_{rq} + \\ - \omega(i_{sq}\Psi_{rq} + i_{sd}\Psi_{rd}) - a_3\omega\Psi_r^2] \qquad (22)$$

$$f_{22} = a_4 a_6 \Psi_{rq} \qquad (23)$$

$$f_{23} = -a_4 a_6 \Psi_{rd} \qquad (24)$$

In order that S1→0 and S2→0 in finite time, the control law is designed such that

$$\begin{bmatrix} \dot{S}_1 \\ \dot{S}_2 \end{bmatrix} = -\begin{bmatrix} k_1 \text{sign}(S_1) \\ k_2 \text{sign}(S_2) \end{bmatrix} \qquad (25)$$

where k1 and k2 are positive constants, sign(.) is the signum function

$$\text{sign}(S) = \begin{cases} 1 \text{ if } S > 1 \\ -1 \text{ if } S < -1 \\ 0 \text{ if } S = 0 \end{cases} \qquad (26)$$

It follows from (19) and (20) that

$$u_{sd} = f'_{12}\left[f_{11} + k_1 \operatorname{sign}(S_1)\right] + \\ + f'_{13}\left[\dot{T}_{ref} + f_{21} + k_2 \operatorname{sign}(S_2)\right] \quad (27)$$

$$u_{sq} = f'_{22}\left[f_{11} + k_1 \operatorname{sign}(S_1)\right] + \\ + f'_{23}\left[\dot{T}_{ref} + f_{21} + k_2 \operatorname{sign}(S_2)\right] \quad (28)$$

Where

$$f'_{12} = \frac{\Psi_{rd}}{2\tau_\varphi a_4 a_5 \Psi_r^2} \quad (29)$$

$$f'_{13} = \frac{-\Psi_{rq}}{\tau_\varphi a_4 a_6 \Psi_r^2} \quad (30)$$

$$f'_{22} = \frac{\Psi_{rq}}{2\tau_\varphi a_4 a_5 \Psi_r^2} \quad (31)$$

$$f'_{23} = \frac{\Psi_{rd}}{\tau_\varphi a_4 a_6 \Psi_r^2} \quad (32)$$

Literature Survey

- **John Y. Hung, "Variable Structure Control: A Survey", IEEE Trans. On Industrial electronics, Vol.40, no.1, 1993.**

A tutorial account of variable structure control with sliding mode is presented in this paper. The purpose is to introduce in a concise manner the fundamental theory, main results, and practical applications of this powerful control system design approach. This approach is particularly attractive for the control of nonlinear systems.

- **V.I. Utkin, "Sliding mode control design principles and applications to Electric drives," IEEE Trans. On Industrial electronics, Vol.40, no.1, 1993.**

This paper deals with the basic concepts, mathematics, and design aspects of sliding mode control. The control algorithms and data processing used in variable structure systems are analyzed. The potential of sliding mode control methodology is demonstrated for versatility of electric drives and functional goal of control.

- **Hoon Lee, V.I. Utkin, "Chattering problem in sliding mode control systems," proceeding of the International workshop on Variable structure systems, 2006.**

This paper discusses the drawback of the sliding mode control that is high frequency chattering due to high frequency switching. The high frequency switching can excite the unmodelled dynamics and make the system unstable.

- **Do Thi Hong Tham," Sliding mode control of Induction Motor", International syposium on Electrical and electronics Eng. , Vietnam, 2007.**

This paper presents a sliding mode controller for induction motor. The controller is developed in the dq co-ordinates. It has two loops: In the inner loop the rotor flux and the motor torque are controlled using the sliding mode approach. In the outer loop the rotor speed is controlled using PID controller. The stability robustness conditions of the controller are carried out to cope with the change in motor parameters.

- **R.Saravana Kumar, K.Vinoth Kumar and K.K. Ray, " Sliding mode control of induction motor using simulation approach", IJCSNS international Journal of computer science and network security, vol.9 no.10 2009.**

In this paper a total sliding mode control schemes of the induction motor are compared with the new adaptive sliding mode control system using Matlab/Simulink. The adaptive sliding mode control system adjusts the bound of uncertainties in real time and also reduces the chattering phenomena.

- **Kanungo Barada Mohanty, " Sensorless sliding mode control of Induction motor", IEEE Trans. 2009.**

This paper demonstrates that invariant regulator and superior servo performance can be obtained, compared to fixed gain controllers through sliding mode speed control of a decoupled induction machine. A speed estimation algorithm is implemented and used in sliding mode control scheme. Sensorless sliding mode control is found to be superior to fixed gain control.

- **Mukesh Kumawat and Dr.J.V. Desai, " Speed control of induction motor using sliding mode controller", IJAECE Journal, vol.1 2012.**

This paper presents the design of a new controller for a vector control induction motor drive that employs an outer loop speed controller using SMC. Several tests were performed to evaluated the performance of the new control method and one can conclude that the new controller law provides high performance dynamic characteristics and its robust with regard to plant parameter variation.

- **B.B Musmade, R.K. Munje and B.M. Patre," Design of sliding mode control scheme for nonlinear processes for improved performance," IEEE Trans.on industrial electronics vol.51 , 2014.**

In this paper , new sliding mode control scheme is presented for control of nonlinear processes. Using nominal system and related bounds of uncertainties, tuning parameters are obtained from reachability condition.

- **B.Bandyopadhyay and Prasiddh Trivedi, " A Simple Reaching law Based Design Method for 2-Siding mode control", in IEEE International Conference on Industrial Technology, 2010.**

The current literature available on HOSM is overly complex and difficult to grasp for a practicing engineer. The purpose of this paper is to present the concept of higher-order sliding mode in a simplified manner. A reaching law based approach for designing 2-sliding controller is explained and evaluated with example.

Research Plan

- The approach of the sliding mode controller is to make each sliding surface attractive, due to this the control law become complicated it defined implicitly by a set of fairly complicated algebraic inequalities.

Objective: To obtain a simple control laws, which make the state of the system attracted to the intersection of the surfaces without necessarily reaching each individual one. The sliding surfaces formulated in these schemes are fixed in the state space.

- Overcome the drawbacks of Sliding mode controller like its discontinuity across sliding surfaces and the chattering problem.

Objective: To obtain the continuous control law for the induction motor control and apply the higher order sliding mode control law to make a system robust.

Objective: A new sliding mode control approaches to the problem of speed sensorless induction motor torque control and induction motor parameter adaptation such problems are commonly encountered in electric drives and many applications such as robotics, electric vehicles and so on.

- The induction motor drive system has model uncertainties, and it is also sensitive to parameter variation, and load disturbances, a robust control strategy based on sliding mode is designed. But, in sliding mode control, torque ripple is significant.

Objective: To obtain the control law which reduce the torque ripple and improve the transient response of the induction motor.

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